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The pathways of dynamic recrystallization in all-metal hip joints[☆]

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Abstract

In the present study metal-on-metal (MoM) McKee-Farrar prostheses of the first generation were investigated by means of transmission electron microscopy (TEM). It was possible to observe the worn regions using a novel taper section preparation technique without producing any artefacts. Thereby, it could be shown that the wear in vivo leads to a reduction in grain size by a factor of up to 20,000. This is achieved by recrystallization via two pathways which act simultaneously within the subsurface regions. One is dominated by the metallurgical characteristics of the material and follows the gradient of the friction induced shear strains from the bulk towards the surface. The other one is merely acting within the tribological contact volume directly at the surface. Both mechanisms lead to a significant increase in strength.

Keywords: Recrystallization; Nanocrystals; Wear; Artificial hip joints

1. Introduction

With approximately 750,000 surgeries per year the total or surface replacement of the natural hip joint is one of the most common surgeries in orthopaedics [1]. Artificial hip joints have been used since 1938 and are nowadays implanted with a high chance of success, e.g. 97% in 2000 [2]. However, the postoperative rate of revisions is still high with 50% in 1996 [3]. Although many different effects like individual medical predisposition or life style and to a much lesser extent clinical mistakes influence the life time of artificial hip joints, the most dominant reason for early failure is still induced by cellular foreign body reactions resulting from the emission of wear particles [4]. Therefore, minimizing wear in the articulating contact areas is still the major goal to attain orthopaedic implants with a longer lifetime.

The tribological demands to achieve clinical lifetimes beyond 15 years are currently fulfilled by four material combinations: metal-on-polymer, ceramic-on-polymer, ceramic-on-ceramic and metal-on-metal. The choice of material does not only depend on the friction and wear properties but is also strongly influenced by the expected lifetime and activity – thus the age – of the patient, the experience of the surgeon and finally also the financial and legal situation of the clinic. In the US, as the world's largest market with about 270,000 total hip replacements each year [2], metal-on-polymer couples are still referred to as the "golden standard". However, a comparison of the wear rates of the different pairings shows that the classic Charnley prosthesis (metal-on-polymer) generally leads to higher clinical wear rates (<500 μm/a) when compared to hard-hard couples such as ceramic-on-ceramic and metal-on-metal joints. The latter are believed to attain very low wear rates of 1–5 μm/a after an intense running-in wear in the order of 35 μm/a. The fact that some of the joints from the first generation of MoM hip joints (e.g. McKee-Farrar prostheses) lasted for more than 20 years, led to a promising renaissance of all-metal pairings. Nevertheless, the metallurgical mechanisms, which contribute to high run-in wear as well as to low steady state wear rates are yet to be understood. Therefore, the present study will focus on the metallurgical investigation of the microstructural changes, which lead to the acting in vivo wear mechanisms of MoM hip prostheses.

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2. Materials and methods

Since the number of retrievals is always limited and – as to the nature of human life style – in vivo wear process takes place under distinctly unidentified parameters (starting conditions, loading sequences, duration, and joint motion characteristics, etc.) specimens from a conventional disc-on-pin (DoP) wear test were included for comparison in order to investigate the impact of mechanically dominated wear mechanisms on the subsurface microstructure. Thus all microstructural investigations were performed on laboratory wear specimens and on retrievals.

2.1. Laboratory wear specimens

Details about the testing equipment and conditions can be found in Table 1. A fixed cylindrical pin with a diameter of 6 mm and a spherical tip (radius: 16 mm) runs against a rotating disc with a diameter of 30 mm. Both are emerged in distilled water. The radius of the as generated wear track was 9 mm and the frequency of testing was 1.77 Hz. A normal load of 5 N was applied resulting in a theoretical maximum Hertzian contact pressure of 370 MPa. Prior to testing, the contacting surfaces were mechanically polished to a R_a value of 0.02 μm. The total sliding distance was 10.4 km corresponding to 30 h testing period. This would be roughly 10 weeks in vivo. It should be made clear that the focus of this additional laboratory study was not to simulate body conditions but to solely investigate and understand microstructural changes under tribologically induced shear stresses. This should be done under the action of mechanically dominated wear mechanisms, which are similar to those in vivo. Certainly the influence of chemically dominated wear mechanisms is not regarded. But with respect to the subsurface shear stresses they might be neglected in a first approach. Incorporating the chemistry will be a substantial part of the authors' future work after the metallurgy has been fully understood.

2.2. Retrievals (in vivo)

Three metal-on-metal (MoM) couplings were chosen from a set of 42 retrieved McKee-Farrar prostheses on the basis of typical wear appearance. The 42 retrievals were in situ for 13.6 years at average (range 1, 3 . . . 22) and none of them was removed for the reason of excessive wear. At the time of removal the prosthesis were carefully rinsed to remove blood and subsequently sterilized and packed. Caution was taken not to touch or damage the bearing surfaces. The entire collection of 42 retrievals has been obtained from a single surgeon and intensively studied by the authors with respect to wear appearances, wear mechanisms and their sequence of acting [5–9]. For this contribution three pairs were solely selected on the basis of macroscopic wear appearances. There was no effort undertaken to control for additional parameters like e.g. manufacturer or time in situ. All three implants showed wear marks in the form of fine scratches or grooves as well as tribochemical reaction layers [9], but no major damage of the articulating surfaces was observed by the unaided eye. Details about brand name, manufacturer and clinical data of those three prostheses are summarized in Table 2.

Table 1
In vivo conditions vs. laboratory test conditions

Parameter	Cup-on-head	Disc-on-pin
Contact geometry	Concave versus convex	Flat versus convex (radius: 16 mm)
Normal force	<2000 N[a]	5 N
Hertzian pressure	<20 MPa[b]	370 MPa
Relative velocity	<0.2 m/s[a] (1 Hz)	0.1 m/s (1.77 Hz)
Temperature	37 °C	22 °C
Sliding motion	Multidirectional	Unidirectional
Duration of loading	7.5 a	30 h (2.8 km sliding distance)
Medium	Synovial fluid	Distilled water

[a] Unsworth [54].
[b] Hodge et al. [55].

Table 2
Clinical data of the retrieved and studied McKee-Farrar couples (from [5])

Element	Couple A	Couple B	Couple C
Alloy trade name	Coballoy	Vinertia	Vinertia
Manufacturer	Dow, UK	Howmedica, USA	Howmedica, USA
Head diameter	35 mm	40 mm	35 mm
Age of patient at revision	80 a	69.4 a	85.3 a
Duration in vivo	7.5 a	17.8 a	19 a

2.3. Materials

The laboratory testing material was a forged low carbon CoCrMo-alloy (Endocast SL, gb Implantattechnologie, Essen, Germany), with a chemical composition similar to that of the cast McKee-Farrar prostheses (Table 3) The major differences lie within the grain size of 600 μm for the cast endoprotheses and of 37 μm for the forged alloy. In addition the latter does not contain as many carbides. However, neither Endocast SL nor the McKee-Farrar alloys belong to the

Table 3
Chemical composition (in wt.%) of the studied low carbon wrought alloy CoCr29Mo6 (Endocast SL) relative to the McKee-Farrar alloys (Coballoy, Vinertia) and ISO 5832/12 [56]

Element	Endocast SL	Coballoy	Vinertia	ISO 5832/12
Cr	27.5	26.4	27.4	26–30
Mo	5.37	4.5	5.4	5–7
C	0.008			<0.35
N	0.17			<0.25
S	<0.002			
Fe	0.26	<1	<1	<0.75
Ni	0.08	2.9	2.3	<1
W	0.01			
Si	0.42	<1	<1	<1
Mn	0.53			<1
Al		<1	<1	
Co	Balance	Balance	Balance	Balance